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Biomass gasification: Still promising? A 30-year global overview

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ABSTRACT

Over the past decades biomass gasification has been regarded as a very promising technology, because of the large potential and the option of advanced applications. In this paper a 30-year overview is presented of the worldwide development of biomass gasification as part of the more general field of gasification, based on both literature and science and technology indicators. The first period of development until the mid-80s is characterized by large interest in coal gasification and domination by the USA. The second period relates more to biomass gasification. It starts in the mid-1990s and is dominated by Europe, although China and Japan are coming up strongly. The technology has been successful in a few niche markets, but largely remains confined to RD&D niches. High-end applications like IGCC and transport fuels have received major interest in research and development. However, biomass gasification is not yet mature enough to be widely applied in the market. It is still in a stage of variation and there has been no dominant design yet. In most markets it is unable to compete with other technologies. We do not expect a breakthrough on the short term, a gradual niche development seems much more likely.

Contents

1. Introduction

A reliable, affordable and clean energy supply is of major importance for society, economy and the environment – and will prove to be crucial in the 21st century. In this context *modern* use of biomass (as opposed to *traditional* use) is considered very

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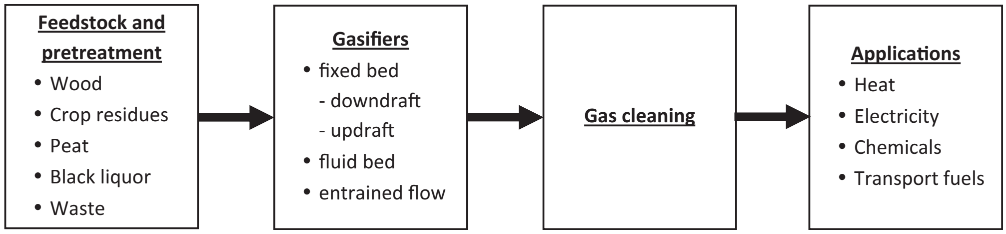

Fig. 1. Gasification technology offers flexibility and enables biomass use in advanced applications.

promising. The promise includes a widely available, renewable and CO_2-neutral resource, suited for modern applications for power generation, fuels and chemicals. Biomass has a distinct advantage over the use of other renewables, like solar cells and wind power, which are restricted because of the intermittent power generation. Biomass is by far the most applied renewable at this moment and a further increase is believed to be possible [1].

Gasification is a clean and highly efficient conversion process that offers the possibility to convert various feedstock to a wide variety of applications, see Fig. 1. It has been considered both in advanced applications in developed countries, as well as for rural electrification in developing countries. As such it has been considered *the* enabling technology for modern biomass use. This raises the question whether it will be able to live up to these lofty expectations.

Gasification can be understood as a thermo-chemical conversion with limited oxygen supply. This results in the production of a producer gas (also called syngas) with significant amounts of carbon monoxide (CO) and hydrogen (H_2) and a low to medium energetic value. In Textbox 1 the basic characteristics of the main gasifier technologies are presented.

Gasification has a long history, with applications in town gas in the 19th and 20th century and a revival of small-scale gasification during World War II, due to an acute shortage in liquid fuels. More recently the oil crisis in the 1970s played a major role in the renewal of interest for biomass gasification. Since then a significant R&D and demonstration effort has been launched in Europe and North America, of which the more recent part has been extensively covered by literature, see e.g. Faaij [2], Knoef [4] and Maniatis [5]. This literature shows a true kaleidoscope of designs. This can be considered indicative for the large interest in the technology, but to what extent has this resulted in a distinct technological trajectory, one that justifies the high expectations?

In this paper we attempt to answer this question and we will assess the future potential of biomass gasification, based on a 30-year overview of the development of this technology. Drawing on evolutionary theories, we will study global developments, which will allow us to make geographically differentiated conclusions and include spill-over between regions. In addition, we will study both coal gasification and biomass gasification, because literature suggests they share many characteristics: general gasifier designs, hot gas cleaning and (foreseen) applications [6,7]. After addressing methodological issues, we will provide an empirical overview based on literature and relevant science and technology indicators. The latter add detail, especially on dynamics, and ensure the coverage of global trends. In the final section we will come to conclusions and reflect on the chosen approach.

Textbox 1. Characterization of gasification technologies

Fixed bed technology: a fixed bed of feedstock is being gasified using a gasification medium, generally air at low velocity. Main subtypes are downdraft and updraft gasifiers, which are mainly applied at smaller scales.
Fluid bed technology: a small fraction of feedstock is added to a much larger fraction of bed material, which is fluidized by a gasification medium (air, oxygen, steam) that flows through the bed at a high enough speed. Main subtypes are the bubbling and the circulating fluidized bed, which are mainly applied for biomass at medium scales.
Entrained flow gasification: small droplets or particles of feedstock are 'entrained' in a flow of gasifying medium – in general oxygen or steam. Also referred to as suspension flow or dust cloud gasifiers. It has been mainly applied at larger scales for coal and petroleum based feedstock.

2. Theoretical framework and methodology

2.1. Evolutionary framework

We will follow an evolutionary approach to analyse technological development. This approach addresses long-term processes that contain multiple product sequences; it is based on the mechanisms of variation, selection and retention. Variation refers to the creation of new designs by engineers and scientists in R&D laboratories or research institutes. This variation is not blind. It arises from firm specific differences in search processes and R&D, in attempts to generate alternatives and seek solution to problems [8]. These search processes are directed by agency, strategies and expectations. History matters, as the process of variation builds on existing products and routines. The variations lead to somewhat different products, which compete in the market. Selection mainly takes place in these markets (sales, profits), although there is also selection on knowledge by communities of engineers and by firms internally and to the extent technologies are socially legitimate as reflected in governmental regulations and social norms. Retention, finally, refers to the mechanisms that retain the reproduction of successful variations, a process of institutionalization [9,10]. In this approach, different technologies can also co-evolve. A specific case are technologies that are rather 'close' and share a specific technology base, as this allows for spill-over and shared technological learning [11]. In our case there are two such cases to consider: the co-evolution of coal and biomass gasification, and of biomass combustion and gasification.

Nelson and Winter [12] considered the directed development of technology in the phase of variation as a sort of coordination within a population of firms (industry, sector). Because of shared routines, engineers in a technological field work in more or less the same direction. Hence, "*sequences of minor variations ... add up to global technological trajectories that proceed in particular directions*." [9, p. 37].

These technological trajectories are not equivalent to focusing on a single technology. Contrary, evolutionary theory assumes that firms will be using somewhat different technologies, characterized by different fitness as expressed in profits. Only over time this will result in a dominant technology and dominant firm(s), as market selection singles out the best performing technology. Another source of diversity are the application of a technology in specific market segments or niches. "*In markets with heterogeneous*

products, there are various user groups that differ in their valuations of a technology's characteristics. In such environments, new technologies can be introduced in niche markets. ... Once introduced, users and producers start learning and will introduce subsequent improvements. Such a gradual process allows the technology to diffuse niche-by-niche." [10, p. 465]. This is especially important, as new technologies often require protection from mainstream market selection to become more competitive and be able to escape lock in – for example from the fossil fuel based economy.

Niches are not only present under heterogeneous market conditions, but can also be socially constructed by actors that are willing to invest time and resources in a new technology, because they believe in its potential [13]. In that case (temporary) protection can come from policy makers through subsidies and regulatory adaptations. The recent strand of literature on Strategic Niche Management (SNM) is building on that idea [14].

As such the evolutionary framework offers the possibility to deal with both diversity and directed development. We will reconstruct the technological trajectory of (biomass) gasification technology by identifying the main variations (designs, actors) and the major drivers and barriers – that is the (anticipated) socio-economical selection environment (niches) that directed the technological development. Special attention will be given to countries, as they provide protection, that is a specific selection environment for technology development, including factors like the presence of biomass and relevant industries, government regulations on energy and waste, and the attitude of the people towards environmental problems. In addition, governments also have more active involvement in innovations processes, by setting RD&D budgets, research agendas and making policy.

2.2. Methodology

For the reconstruction we will apply two overlapping yet distinct methods. The first is a literature study, including overview articles, government reports, commercial status reports and books. A significant part of this literature has been written for IEA Bioenergy, an organization with the aim of improving cooperation and information exchange between countries. The literature offers a great detail on developments, including operational capacity, current status, socio-economical context (driving forces and barriers) and expectations and visions. The focus is mainly on the most successful and promising technologies. Detailed publications on technological developments have *not* been included.

Second, we will present results of science and technology indicators related to biomass gasification. This offers the possibility of cross-examination of trends identified from literature. The indicators present the dynamics over the full population, including the minor variations that add up to global trajectories. It also allows to identify relevant companies, research institutes and countries.

Science and technology (ST) indicators are widely used. Indicators that we will use are publications to measure research activities or scientific productivity and patents to assess knowledge based innovation and commercialization activities. Both are long-term output indicators of the RD&D process. The content of patents and scientific articles are hardly overlapping, they are complementary to each other [15,16].

The general patenting and publishing rate have increased significantly over the years. Our constructed time series have been corrected for that and represent trends as if overall patenting and publishing rate had been stable – thereby only indicating differences in interest in (biomass) gasification. With respect to geographical coverage, patent sets show the tendency to over-represent domestic patents and patenting intensity is not equal for all regions. We used patent sets from multiple offices, thereby reducing this geograhical bias.

3. Gasification

An overview of large operational gasification plants (of capacity over 100 MW_e electric equivalents, commercial industrial scale) has been presented by US DoE [17], US DoE [18], US DoE [19], US DoE [20]. They include 144 plants and 427 gasifiers. The market is dominated by coal and petroleum based gasifiers. At least 15 different gasification technologies are in operation, of which three technologies are dominant: Sasol Lurgi, GE Energy (former Texaco) and Shell. The latter two are dominating recent developments and are examples of entrained flow gasification. Since 2001 new plants have mainly been built in China. Gasifiers in Europe are mainly located in Germany.

The total capacity shows a growth until 1985, followed by a decade of market stabilization, to start growing again from 1993 onwards. Fig. 2 shows the development of accumulated operational capacity for the five dominating applications. Leading applications are Fischer Tropsch liquids (29% of 2006 capacity, 4 plants) and power production (24%, 22 plants). The production of chemicals like ammonia, methanol and hydrogen is steadily increasing. Other minor applications – not shown in the graph – are oxochemicals, carbon monoxide and others. All applications except integrated gasification combined cycles (IGCC) have already been applied before the 1970s.

The few Fischer Tropsch installations are typically very large plants, located mainly in South Africa (Sasol). They were built in the late 70s and early 80s under the Apartheid regime, when South Africa faced an international oil embargo. Gasification in combination with Fischer Tropsch synthesis made it possible to convert the South African coal reserves into fuels and chemicals.

Electricity production has been a late success, only gaining real significance in the late 1990s when IGCC started to find commercial application. IGCC made a coal-to-power conversion possible that was more efficient and less polluting. It has been mainly applied in Europe.

The production of ammonia takes place in India and China. Ammonia is used for the production of fertilizers. The production of methanol is located in Germany and China. Its largest use by far is in the production of other chemicals and biodiesel. The two largest uses for hydrogen are in fossil fuel processing (e.g. hydrocracking) and ammonia production.

The production of Substitute Natural Gas (SNG) has not been included in Fig. 2. SNG is methane that is produced by a gasification reaction, opposed to natural gas that is produced at oil and gas fields. Its production was especially considered in the USA in the 1970s and early 1980s. It included the development efforts by Exxon on a catalytic fluid bed technology. Another development effort resulted in the Great Plains plant in the USA in 1984 that

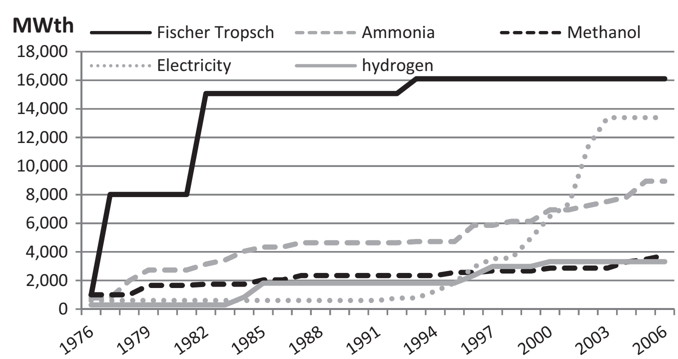

Fig. 2. Accumulated capacity of main applications of gasification [*Data*: [20]].

proved to be uneconomical. Developments have stagnated since [21–23].

Most of the research and development of coal gasification took place in Germany and USA, although the UK and Japan also played a role. Many developments in coal gasification are based on classical German coal gasification technologies: the Lurgi moving bed, the Winkler fluid bed and the Koppers Totzek entrained flow processes. Major developments in Germany were still going on in the 70s and early 80s. For the USA coal utilization for power production was and still is the core to its national energy strategy. It was a motivation to start development programs for coal gasification in the 70s after the first oil crisis [22,23].

According to Harmsen [22] three different periods can be distinguished in the development of coal gasification between the 1970s and the 1990s. In the 1970s many companies started to develop their own processes and aimed at various applications. This period has been dominated by the two oil crises resulting in high prices for oil and strong concern by countries about self-sufficiency and fuel diversification. The second period covers the 1980s, in which a number of process developments were stopped that became economically unattractive due to decreasing oil prices. Remaining developments focused on IGCC that promised to be superior on environmental performance at similar costs compared to conventional coal-fired plants. This was considered especially important, as nuclear based electricity production was no longer considered a promising option. Also environmental awareness increased and climate change was first put on the international political agenda. In the third period, in the 1990s, the focus diverged again, considering more fuels and applications. However, IGCC had reached the stage of commercial demonstration. The period can be characterized by liberalization and deregulation of the electricity markets. This resulted in a strong preference for gas based power production, since it was a cheaper, cleaner and a reliable and proven technology. However, the liberalization also offered opportunities for gasification technology. An example is the polygeneration in refineries, in which oil residues are gasified to produce hydrogen and steam for the refinery and in addition electricity is produced and supplied to the grid [19].

More recent driving forces are the expanding economies, in particular China, the growing concerns regarding CO_2 emissions and the volatile fuel prices [18,19]. China has de facto become the world's test-bed for large-scale coal utilization processes. According to Henley [24], key economic factors are driving China to coal: very low costs of coal and labor and advantageous state financing. However, the largest contributing factor is the strong support from the Central Government and from provincial and local level. Coal gasification has not only found application, but has also been subject of Chinese research since the late 1990s [25].

Ongoing concerns regarding CO_2 emissions have resulted in both barriers and opportunities for further development. They are a fertile soil for anti coal sentiment. However, if carbon emissions become increasingly regulated, gasification based technologies will benefit from this: they offer increased efficiency and allow for carbon capture and storage (CCS).

Decisions to move forward with gasification projects also depend highly on costs and prices of energy. Gasification applications are most directly in competition with natural gas based technologies, both for power applications as for the production of ammonia, methanol and hydrogen. Between 1990 and 2000 natural gas was available at a relative low costs, after which costs increased with a factor three until 2007. This has improved the economical competitiveness of gasification technology [18,19].

The US Department of Energy is continuing its gasification program, both research and development, to improve the overall economical and technological competitiveness, also in advanced applications. Each of the crucial components of the gasifier is subject of study, offering potential for improvement [19,26,84].

4. Biomass gasification

4.1. Overview

In biomass gasification mostly wood is considered as feedstock. However, also peat, black liquor and rice husk gasification have been demonstrated. Black liquor is a byproduct of the paper industry, a lignin-rich mixture of cooking chemicals and dissolved wood material. Rice husk gasification has found application in Asia [7,27].

Canada, Finland, Sweden and the USA have been initially involved in the development of biomass gasification. Each of them has large woody biomass and/or peat resources. In the 1970s especially the USA fulfilled a leading role in response to the disruption of oil supply and high oil prices. This involved research and rapid development of gasification concepts. The potential to substitute natural gas or transportation fuels was viewed as being very important. However, initial applications were less advanced and focused on heat and power applications. Energy research in the 1980s shifted focus to long-term high risk research. Most financial incentives that were needed to stimulate the commercial use of biomass energy were eliminated – and so were many projects and plants [28–30].

Circulating fluid bed (CFB) gasifiers have been first applied in the early 80s by Lurgi (Germany) and Ahlstrom (Finland, now Foster Wheeler). According to Basu [31] both were based on their respective CFB combustion designs that were developed separate from the large government funded programs. Lurgi used its experience in ore roasting fluidized beds. Ahlstrom, a Finish engineering company and established producer of pulp and paper products, became interested in the technology as a method of burning a wide range of 'difficult' fuels for this sector – including biomass and bark [32].

The 1990s brought increased awareness of climate change, which resulted in a renewed interest in biomass gasification [6,7,28,34]. While some developments in the USA continued, European countries became increasingly involved. Germany and Austria have joint Sweden and Finland as leading countries, while many others became involved in development and implementation, including Netherlands, Italy, UK, Switzerland and Denmark [35–37]. Especially in countries with strong support for renewables and with availability of biomass, the development of biomass gasification has become an established practice [2,27]. By 2005, the status of the technology was such, that there was significant interest for gasification but hardly any new commercially projects were implemented [4].

A gasifier plant not only consists of a gasifier, but also includes feedstock pretreatment and feeding, gas cleaning and the end-use application. Over time each of these processes has been subject of continued research and development, with addition of the subjects of systems integration and scientific understanding of the gasification process. Since the late 1990s a significant amount of effort has been focused on gas cleaning [5,6,37,38].

4.2. Applications

Modern use of biomass has been mainly based on combustion. By 2000, 40 GW_{el} of electricity production capacity was installed worldwide and 200 GW_{th} of heat production capacity – over 90% of which was based on combustion. It has been successfully used in the lumber, paper and pulp industry and the cane-based sugar industry – sectors that also provide a huge potential for biomass

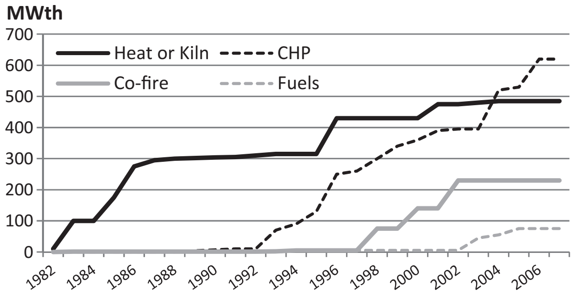

Fig. 3. Accumulated capacity of main applications of biomass gasification [*Data*: [39]].

gasification. Biomass gasification is applied on a much more modest scale, totaling about 1.4 GW_{th}. Gasification has the advantage over combustion of more efficient and better controlled heating, higher efficiencies in power production and the possibility to be applied for chemicals and fuel production [1].

An overview of accumulated operational capacity of biomass gasifiers for different applications is provided in Fig. 3, based on Hellsmark [39] who created a database for his research on biomass gasification in Europe. Details on the database have not yet been published. The overview is in line with developments described in literature that also provides more detail on its current status (see [1,2,5,7,27,37]). All applications of biomass gasification show an increase over time. This increase is most significant for CHP, which has become the main application.

Since the 1980s gasifiers for heat applications have been installed at lime kilns in the paper industry and cement kilns: a relative simple niche application in a sector that combined availability of feedstock and heat demand. Initial applications can be found in the USA, Sweden and Finland. The application has achieved commercial status, meaning that guarantees are supplied and the technology is competitive, but it shows limited diffusion.

The heat applications were followed in 1990 by the first combined heat and power (CHP) applications, using diesel or gas engines. Deployment has been limited due to relatively high costs, critical operation demands, and fuel quality. It has been difficult to find areas where both heat and electricity feed-in tariffs are high. Deployment has often been related to national support, like the Swedish carbon tax and the Austrian CHP program.

IGCC became the centre of attention in the 1990s, mainly in Europe, in response to the promising results for coal IGCC. This is especially true for Europe. The technology promised high electrical efficiency at modest scales combined with modest capital costs. This resulted in a significant R&D effort and a few demonstration plants. But over time these plants have been canceled or shut down. Besides some technical issues this has mainly been due to the innovation gap: the unattractive phase between demonstration and market application characterized by an unproven technology available at high costs.

Since 1998 biomass gasifiers have been implemented at coal-fired power stations for indirect co-combustion: the biomass is gasified, after which the resulting producer gas is combusted together with the coal. This way biomass is introduced in the power industry with a minimum of potential risk to the boiler and to the quality of by-products, and this can be done at reasonably high efficiencies and limited costs. Interest in larger biomass co-firing shares and utilization of more advanced options is increasing. However, in practice often direct co-combustion is preferred, in which biomass is not gasified but directly combusted together with the coal.

The latest development is a shift in interest to transport fuels (second generation fuels produced by gasification). These fuels offer a much better greenhouse gas performances and less competition with food compared to first generation biofuels. In addition, the transport fuels are high value energy carriers that might justify the use of (more expensive) cultivated biomass.

Already in the 80s, methanol, DME, Fischer Tropsch liquids and hydrogen played a role, both in Europe as in the USA. For example, methanol production was tested and developed in France, Sweden and Canada. In Europe only recently, pushed by the EC biofuel directive (2003), attention for those routes is evident again in research programs of the EC (6th and 7th framework program) and countries like the Netherlands, Sweden and Germany. Current applications can best be qualified as research and demonstration and include the partnership involving Choren Fuel and the Schwarze Pümpe plant in Germany. The technological challenges are complex, since gas cleaning needs to be very effective in order to protect downstream catalytic gas processing equipment. There is a high confidence that once clean syngas is available, known process technology for producing the fuels can be applied [2,5,27]. Also in the US biomass-derived fuels have received increasing attention in recent years, including a mandatory setting for renewable fuels. However, there is a focus on cellulosic ethanol, which does not require gasification. Nevertheless some research is going on for biomass gasification to produce clean syngas for the production of ethanol or other fuels or chemicals [40].

Advanced applications require significant upscaling: for IGCC a typical commercial scale is considered of 30–200 MW_e; 50–200 MW_{th} for the chemical sector and several 1000 MW_{th} for transportation fuels. The required scales are the effect of market size and economies of scale (costs minimisation). Besides the challenge of scaling up, this presents a mismatch with the dispersed availability of biomass of low energy density: larger plants result in higher feedstock costs because longer transport distances are involved. This can be overcome by converting biomass to an energy carrier with higher energy density, for example by local pyrolysis plants. Another option is to focus initially on applications that require less biomass capacity: co-gasification with coal or co-combustion of producer gas with natural gas in a combined cycle. A third option is the cogeneration of multiple products in a pulp and paper mill. This would offer product flexibility and added value for a sector that provide the feedstock themselves [41,56,2].

Another problem of modern applications are the high initial investment costs, especially of the first plants, in combination with the risks involved. To achieve a reduction in capital costs for IGCC plants requires at least several successful demonstration plants, which themselves would be uneconomical. However, the liberalization of the energy markets has resulted in decreased direct support from national governments for technology development and of reducing investments of the energy sector in risky technology with long term benefits. This has stalled the application of the promising application [2,27,42]. A similar effect can be expected in fuel applications, since these require even larger investments and are considered more risky [43,44].

Three applications have not yet been discussed. The first one is high temperature fuels cells, which have only been considered in research [6]; the second one is waste gasification; and the third one are applications in developing countries.

Waste gasification found application in Japan since 1997. Main drivers have been the shortage of landfill and the policy to avoid incineration, emissions of dioxins and to increase plant size. The policy has been supported by technology development and demonstration programs. All leading Japanese thermal process companies now offer gasification solutions. The Nippon Steel (updraft) and Ebara (fluid bed) technology are fully commercial [45,46]. However, these technologies in general focus more on the production of manageable secondary waste products (solidified

Table 1
Leading small scale (updraft and downdraft) manufacturers and technologies in developed countries [55,85].

	Technology/company	Country	Gasifier
1	Bioneer (now Foster Wheeler)	Finland	Updraft, heat
2	PRM Energy Systems Inc. (PRME)	USA	Updraft, heat/power
3	Babcock Wilcox Volund	Denmark	Updraft, heat and power
4	REL Waterwide technology	New Zealand	Downdraft, heat
5	Chiptec Wood Energy Systems	USA	Downdraft, heat
6	Fluidyne Gasification	New Zealand	Downdraft, power
7	Xylowatt	Belgium	Downdraft, power
8	AHT Pyrogas Vertriebs	Germany	Double zone, heat and power
9	COWI/DTU 'Viking' gasifier	Denmark	Multi stage, electricity
10	Biomass Engineering	UK	Downdraft
11	ITI Energy	UK	Fixed bed, proprietary design
12	Puhdas Energia Oy	Finland	Downdraft
13	Host	Netherlands	Fixed bed
14	Condens Oy – Novel gasifier	Finland	Fixed bed, counter current bottom

ash) than on energy recovery [27]. Another country with significant experience in waste gasification is Germany.

For developing countries the promise of rural electrification and local development has been a major driver for projects, a.o. by the World Bank and Western countries in the 1980s. These attempts were not very successful [47]. Main developments over the past decades can be found in India and China [48], that is for development, manufacturing, application and diffusion of the technology. Hundreds to thousands of small fixed bed gasifier systems have been installed [49,50]. Applications remain troublesome, with problems regarding tar, operation, maintenance and economical feasibility. Ghosh et al. [63] and Verbong et al. [51] conclude that small scale rural electrification might not be the best way to introduce gasification technology in developing countries, especially India. Thermal applications are already applied and have a better track record. And medium scale power generation, either in industry or rural grid connected, is likely to face less difficulties (economical, technical and practical).

4.3. Technologies

In contrast to coal gasification, which is dominated by entrained flow technology, in biomass gasification a range of technologies has been applied. At the end of the 80s and the beginning of the 90s, downdraft and updraft gasifiers with capacities of less than 100 kW_{th} and up to a few MW_{th} were developed and tested for small-scale power and heat generation [2]. More recently the downdraft technology has become dominant, especially for power applications, due to its low tar content in the producer gas [35,52]. Major applications can be found in India and China – as was discussed above.

Extensive lists of manufacturers can be found in literature (see [49,57] (China); [51] (India); [52,53,87,54,55]), many of which are small companies with limited resources and some with a regional orientation on the market. Quite typical for this stage of market formation are takeovers of companies and technologies and new companies entering the market. For most equipment suppliers gasification is not their core business, and plants are not mass produced. A selection of leading companies (most applied or advanced) for developed countries is presented in Table 1.

In the case of nearly all medium-to-large scale gasification plants for power production, the preferred technology has been atmospheric circulating fluidized beds (CFB): it can handle a high throughput, is relatively easy to scale up and is capable of accepting a wide range in fuel quality – both in particle size and in ash properties [27,35,52]. However bubbling fluidized bed systems (BFB) are also still applied. Air blown gasifiers are preferred for heat and power applications, while the more advanced applications require oxygen blown gasification (and therefore an oxygen plant). Pressurized systems are considered for larger capacities and for

Table 2
Leading gasification concepts for large scale or advanced cycles [85,87–89,27].

	Company	country	Gasifier
1	Gas Technology Institute (GTI) - Renugas technology (Institute of Gas Technology (IGT))	USA	BFB, air/oxygen blown, pressurized
2	Repotec Umwelttechnik/Austrian Energy and Environment (Güssing CHP plant)	Austria	BFB, indirectly heated, steam blown (CFB air combustor)
3	Enerkem Technologies Inc. - BIOSYN technology	Canada	BFB, air/oxygen blown, pressurized
4	ThermoChem (Manufacturing and Technology Conversion International (MTCI))	USA	BFB, pulse enhanced, indirectly heated, steam blown, atmospheric (also) black liquor gasification
5	Envirotherm GmbH, part of Allied Environmental Solutions Inc. (Lurgi technology, BGL at Schwarze Pümpe)	Germany/USA	- BGL fixed bed, slagging bottom, pressurized; - CFB, atmospheric
6	Rentech Inc. - Rentech-Silvagas technology (Battelle Columbus Lab/Future Energy Resource Corporation (FERCO))	USA	CFB, indirectly heated, steam/air blown, atmospheric/low pressure
7	TPS Termiska Processor AB (ex Studsvik Energiteknik AB)	Sweden	CFB, air blown, atmospheric
8	Foster Wheeler (ex Ahlström)	USA/Finland	CFB, air blown, atmospheric/pressurized
9	Ebara - Twin Rec UEP Gasification technology	Japan	CFB, gas to slagging combustor, air blown, waste
10	Choren Industries GmbH - Carbo V technology (Deutsche Brennstoff Institut)	Germany	Entrained, involving pre-gasification or pyrolysis, air/oxygen blown, sewage sludge
11	Chemrec A.B. (ex Kvaerner Pulp & Paper)	Sweden	Entrained, air/oxygen blown, black liquor
12	Thermoselect S.A.	Switser land	Pyrolyzer and entrained char gasifier, oxygen blown, waste
13	Siemens Fuel Gasification Technologies GmbH (Future Energy, BBP, NOEL-KRC, Deutsche Brennstof Institut)	Germany	Entrained, oxygen blown, pressurized
14	Energy Products of Idaho	USA	BFB

Table 3
Coal versus biomass gasification: a summary.

	Coal gasification	Biomass gasification
Preferred technology	Entrained flow	Updraft (small, mainly heat); Downdraft (small, mainly power) Circulating fluid bed; (large) Entrained flow (large, fuels and chemicals)
Main applications (niches)	Fischer Tropsch (South Africa); IGCC power; poly-generation in refineries; China (ammonia, methanol)	Heat; Combined heat and power; Co-combustion; IGCC (research); Fuels and chemicals (research); Rural electrification/developing countries; Waste gasification
Scale	100–1000's MW_{th}	0.05–10's MW_{th}
Dominant suppliers	Lurgi, GE, Shell	Multiple
Dominant countries	USA, Germany, China	USA, Finland, Sweden, Germany, Austria; Japan (waste); China, India (small scale)

IGCC, fuels and chemicals – in these cases the final conversion will take place under pressure anyway. Advanced applications require a strict gas cleaning.

A specific application in fluid bed technology is indirectly heated gasification, characterized by a separate gasification and combustion reactor/zone. In general, these gasification reactors are steam blown, which results in a higher heating value of the produced gas without the need of oxygen. This requires an air blown combustor to provide the required heat to keep the gasification reactions going. A disadvantage is the increase in complexity of the installation.

Also oxygen blown entrained flow gasification is considered – the preferred technology for coal gasification – since it has the advantage of operating at very large capacities and producing clean syngas. However, this will require significant pretreatment of the biomass (pyrolysis or CFB gasification), since entrained flow systems only gasify very small particles.

In the last decade a wider variety of technologies has found application, like pressurized and entrained flow gasification. Also plasma gasification for waste and gasification in supercritical water of wet biomass (like sewage sludge and pulp waste) has been further developed. Leading suppliers of large scale and advanced gasifiers are presented in Table 2. Heerman and Schwager [87] emphasize that for different market segments and feedstock also different processes are leading. Especially Foster Wheeler (Europe) and Ebara and Nippon Steel (Japan) have realized several gasifiers [27,45].

4.4. Conclusions

The overview presented up till now had a focus on existing (demonstration) plants and current status. Developments in gasification for both biomass and coal are summarized in Table 3. The technology has been successful in a few niche markets, but in general still is confined to RD&D niches.

The literature research has been limited in its description of the RD&D stage. In addition it is lacking detail on demarcation of relevant time periods, the shift in development efforts over different nations and the role of India and China. In the next section we will try to fill these gaps by using science and technology indicators.

5. Science and technology indicators

Patent indicators have been derived from datasets of the United States Patent and Trademark Office (USPTO, [58]) and the European Patent Office (EPO, [60]). In addition the datasets of patent offices of Japan, China and India have been analyzed in less detail [60–62]. C10J3 is a patent class of the World Intellectual Property Organisation that covers patents on the production of combustible gases containing carbon monoxide from solid carbonaceous fuels. This class is most representative for gasification, as can be concluded from sampling of patents using a variety of key words. Within this class we have made differentiations based on key words towards biomass and gasification technologies. Applications are checked upon in combination with the stem 'gasif' or a syngas synonym.

Articles on biomass gasification are checked upon by using Web of Science by Thomson Reuters [59]. Web of Science is an international multidisciplinary index for journal articles in all sciences. It encompasses references to articles of over 8500 journals and thereby is one of the most complete databases available. Time series are constructed for several queries related to gasification ('gasif*'), gasification technologies, feedstock ('biomass or wood') and applications. Applications are checked upon in combination with the stem 'gasif' or a syngas synonym. All were 'Topic' searches, which means that the engine searches within the title, abstract and keywords.

5.1. Dynamics: intensity over time

For both patents and publications, trends are shown over time. The results are presented in Fig. 4 for gasification and in Fig. 5 for biomass gasification. The maximum for each indicator is indexed at one.

Trends on gasification show one active period, starting in the 70s and lasting until 1985 (patents) – 1990 (publications). For

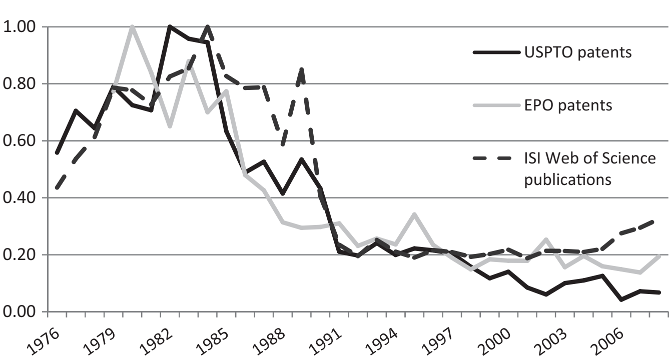

Fig. 4. Gasification, intensity of indicators over time (*Data*: [58–60]).

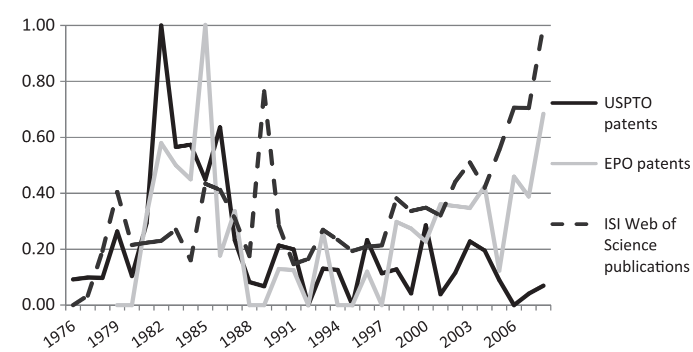

Fig. 5. Biomass gasification, intensity of indicators over time (*Data*: [58–60]).

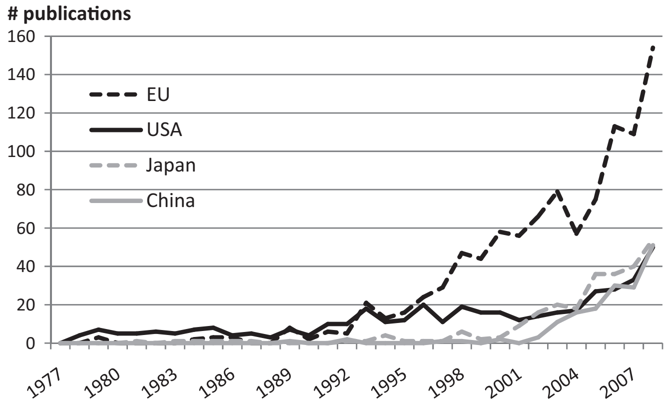

Fig. 6. Geographical distribution of publications on biomass gasification (*Data*: [59]).

biomass gasification two relevant periods can be identified: the first one between 1981 and 1988, with a limited contribution from publications; and the second one from 1998 onwards including the 2008 peak. The USPTO dataset does not show this second peak – probably due the decreasing activity in the USA, as will be discussed in the next paragraph.

Concerns on climate change are presented in literature as being the major driving force for the renewed interest in biomass gasification since the 1990s. These concerns have been articulated only recently (2002–2006) on a limited scale in the USPTO and Web of Science datasets.

5.2. Relevant countries

In the USPTO and EPO patent sets three countries are dominant: USA, Germany and Japan. Apparently these countries hold the relevant industry – possibly with the recent addition of China that scores well on publications and in the Chinese patent set.

Web of Science on publications provides a better worldwide coverage. It shows an increasing interest in biomass gasification: both the total number of countries increases (*the base*) as well as the number of countries that have a significant amount of publications (*the top*). Fig. 6 presents the geographical distribution of publications on biomass gasification over time.

The figure shows that until 1988 the USA is dominating. Since 1997 Europe has become leading and the differences with other regions have increased ever since. Japan has only recently contributed to publications. These trends are in line with trends in patents.

Chinese publications are also of recent date. China is hardly present in the USPTO and EPO datasets. However, Chinese patents confirm that attention for biomass gasification, although rather limited, has been coming up since 2000. China scores much better on gasification in general. Over half of the Chinese patents for both gasification and biomass gasification is held by Chinese companies – indicating a strong Chinese development effort.

India has been publishing on biomass gasification already since 1989 and takes now a 6th position in Web of Science. However, Indian companies hardly patent on gasification, not in India nor abroad.

Literature suggest that for specific feedstock distinctive development paths are in place with specific countries involved. Therefore these have been assessed in Web of Science – see Table 4. They show domination by USA and Japan, with other countries involved for specific feedstock. Note that in this case the overall contribution of the EU has not been taken into account, only of its member states.

5.3. Companies and institutes

With respect to companies involved in gasification USPTO and EPO datasets are very consistent: Texaco and Shell score best with their respective technologies that currently dominate the market for coal gasification. Other companies in the top include: Metallgesellschaft (now marketed by Envirotherm) that developed the Lurgi fixed bed technology (applied in South Africa) and fluid bed technology; Exxon that was developing a catalytic fluid bed coal gasification process to produce SNG in the late 70s and early 80s; Krupp Koppers (now Uhde) that developed the PRENFLO entrained gasification process; and Foster Wheeler that worked on fluid bed gasification and is market leader in fluid bed combustion. In addition, in the USPTO patent set also the US Department of Energy is present as well as Combustion Engineering (now part of Alstom), whereas in EPO patent set the Japanese Ebara and Mitsubishi Heavy Industries take a prominent position.

For biomass gasification the relevant companies are not that clear. About 80–85% of the patents are held by companies that only have 1 or 2 patents. Therefore we conducted a reversed search: for all companies in Tables 1 and 2 we checked the datasets on their presence. Only a few companies involved in small-scale gasifiers hold patents. In contrast, most companies involved in large-scale gasifiers hold patents, but they refer limitedly to biomass.

Web of Science shows a much broader interest among research institutes. An overview of leading institutes is presented in Table 5. On biomass gasification the Chinese Academy of Science is leading, followed by a broad range of institutes. The dominance of Europe since 1997, as was clearly shown in Fig. 6, is hardly present in Table 5. Apparently in Europe a large number of smaller institutes have been publishing, limiting the impact per institute.

5.4. Gasification technologies

We have searched USPTO and Web of Science datasets on technologies; the EPO search engine Espacenet does not support such extensive queries. Technologies considered include updraft, downdraft, fixed bed, fluid bed (or Winkler) and entrained flow gasification. In general, all technologies follow similar trends over time, although minor variations do occur. Apparently, all are steered by similar driving forces leading to similar dynamics. Downdraft and updraft technologies receive rather limited hits.

Most indicators show major intensities prior to 1986–1990, followed by a dramatic decreased. For patents, this decrease roughly continued ever since – possibly due to the lack of US developments. In contrast, publications show a steady increase. Most recent levels (2008) match the levels of the early 80s. Levels

Table 4
Dominant countries involved in the gasification of different feedstock (*Data*: [59]).

Biomass	Wood	Peat	Black liquor	Municipal waste	Agricultural	Sludge	Rice husk
USA	USA	Finland	USA	USA	USA	USA	India
Japan	Japan	USA	Sweden	Japan	Greece	Japan	China
China			Finland		Turkey		Canada
					Spain		

Table 5
Rank of top institutes in biomass gasification. First mentioned is rank, followed by number of publications between brackets (*Data*: [59]).

	Gasification	Gasification biomass	Fluid bed	Fluid bed biomass	Fixed bed	Fixed bed biomass
Tohoku University (JP)	1 (192)					
Chinese Academy of Science (CN)	2 (181)	1 (69)	1 (71)	1 (34)	2 (26)	4 (9)
Pennsylvania State University (USA)	3 (147)					
Consejo Superior de Investigaciones Científicas (ES)	4 (127)				5 (12)	
Hokkaido University (JP)	5 (92)		5 (29)		3 (20)	2 (14)
Forschungszentrum Karlsruhe (DE)		2 (37)				
Nationale Renewable Energy Lab (USA)		3 (37)				
University of Tsukuba (JP)		4 (37)	4 (33)	3 (33)		
University Complutense Madrid (ES)		5 (35)	3 (34)	2 (34)		
Monash University (AU)			2 (34)	5 (19)	1 (29)	1 (18)
Huazhong University of Science and Technolgy (CN)					4 (14)	3 (11)

of publication on biomass technologies, which were hardly present prior to 1990, have taken off. Only updraft technology seems to be lagging behind.

In publications USA, China and Japan dominate on most technologies, both in general as for biomass. For updraft and downdraft technologies also India is relevant. In patents USA and Germany dominate – as is to be expected given their dominance in patents.

5.5. Applications

USPTO and Web of Science data have also been searched for a variety of applications relevant for gasification. These included the production of methanol, ammonia and hydrogen and the application of IGCC, Fischer Tropsch for transport fuels and electricity production involving engines. Total hits differ widely per application.

USPTO patents show most hits prior to 1990, but with a very strong peak for the period 2003–2006 that disappeared as fast as it came. This peak is present for all applications and for both biomass and non-biomass. Many patents have mentioned multiple applications. Major independent trends in the peak have been those for fuel cells and for Fischer Tropsch fuels. In general, the share of biomass increased.

Web of Science publications mainly score after 1990, with a strong increase after 2004, including publications on biomass. USA is leading on most applications, both in general as biomass related. China does well on Fischer Tropsch and hydrogen, Japan on all applications – but both show limited hits on biomass.

In addition two specific trends are worth mentioning. SNG has been developed in the 70s and show a decrease in patents and publications ever since. However, publications suggest a renewed interest since 2005 of biomass based SNG. IGCC is only scoring since 1990, with a peak around 1998 and continued scoring since. Both trends are consistent with literature.

6. Conclusions and discussion

6.1. Conclusions

We included in this study both biomass and coal gasification, as literature suggests that their developments are closely linked. As we have shown, both are subjected to similar driving forces: availability of feedstock (either coal or biomass), prices of fossil fuels and concerns regarding disruption of supply and global warming. As such some synergies can be expected. However, coal and biomass show rather different characteristics: biomass is more fibrous and reactive and has a lower density and ash fusion temperature [4]. This has resulted in the selection of different gasification technologies and, as a result, the involvement of different manufacturers. On a practical and industrial level the linkage has been limited.

Another relevant dimension is the scale of application. The development of entrained flow gasification of coal and the fluid bed gasification of biomass involve global players that serve a global market. However, markets for biomass gasification have been highly depending on niche applications and government support; therefore, the application of this technology still is confined to the national level. For small-scale fixed bed gasifiers, in which a wide variety of manufacturers are involved, there is not (yet) a global market. This technology seems to be driven more by local developments that are not very well represented by patents and scientific articles.

In biomass gasification, two equally relevant periods can be distinguished. The first one, from the 70s until about 1987, is a response to the oil crisis, mainly led by developments in the USA. In this period biomass gasification is part of a more general interest in gasification. Remarkably, Lurgi and Foster Wheeler have developed successful concepts outside the large government supported programs of this period. A second period of activity takes off in the late 1990s and focuses mainly on biomass gasification. Concerns regarding climate change are a major driver. Europe has been dominating these developments. After 2000, Japan and China rapidly are emerging as important players in this field.

We characterized the developments in (biomass) gasification as a process in which the technology has been successful in a few niche markets, but in general still is in an early stage of development, see Table 3. Coal gasification has not yet become a mainstream technology and is open for improvement. However, it has found significant application in the market on a commercial scale: for power production by IGCC in Europe, poly-generation in refineries and in a variety of applications in China. The market has selected a dominant technology and a few dominant suppliers have emerged.

Biomass gasification is less mature. Applications for heat, co-combustion in coal plants and combined heat and power show limited market penetration and some are depending on government regulation and support. High end applications like IGCC and transport fuels (Fischer Tropsch, fuel cells) are considered very promising and received a lot of attention recently in research and demonstration. The required end-use technologies are apparently not the problem, since most have been applied in combination with coal gasification. Technological hurdles for biomass gasification mainly include scaling up, tar reduction and gas cleaning. Also the technology needs to become more economically competitive, as the case of IGCC showed. Downdraft gasifiers and atmospheric air blown circulating fluid bed gasifies are the preferred technologies. However, a much wider range of technologies is considered. Market leaders for fluid bed technology, Foster Wheeler and Ebara, have realized only a limited number of plants. Fixed bed technology found wider application in India and China, but their market share remains low. Based on this, the stage of development of biomass gasification can best be characterized as one of limited niche development.

Biomass gasification has demonstrated great flexibility in adapting to the requirements of different niches. However, this also holds the disadvantage of lack of focus and built up of momentum. This is strengthened by the very diffuse profile of the biomass industry that groups together the forestry industry, boiler manufacturers, farming and agriculture, etc. And only relatively recently, international trade in biomass resources has become part of the portfolio of market dealers of fuels – a requirement for entering the major energy markets [1].

6.2. Discussion

The use of science and technology indicators requires a critical reflection, as the data selection and the procedure for correcting for the growth in patenting and publishing rate are somewhat ambiguous – they are open for slightly different outcomes. However, the long-term trends presented here are robust, as these are that clear that they would not be affected by small variations. In addition, also the use of multiple indicators strengthens the conclusions.

Also several subjects can benefit from more detailing: the downdraft and updraft systems that are described rather limitedly by patents and publications; and the developments in China and India, which remain somewhat underexposed due to the gap in literature.

Biomass gasification has been profiled as being CO_2-neutral, having a high potential, improving security of supply, being able to provide power, chemicals and fuels. The promise of advanced applications has been important in both periods of development. However, the technology has mainly found application for heat and power and only on a limited scale.

To live up to the high expectations the application of biomass gasification will have to expand. Although the advantage over conventional coal technology is clear, this is much less the case when compared to the use of natural gas or biomass combustion. In the market these latter have been the preferred options in recent years: natural gas for power, ammonia and methanol production; and biomass combustion to convert biomass to power or heat. This illustrates the fact that different technologies co-evolve, where (changes in) one technology affects the (commercial) fitness of other technologies. Proponents of biomass gasification often tend to ignore this when they articulate the high expectations for biomass gasification.

A successful application will also be largely depending on the drivers: if the reduction of greenhouse gas emissions has the highest priority, biomass combustion might be the easier and preferred option; if it is about producing renewable and climate neutral biofuels or chemicals biomass gasification becomes relevant; if it is about dealing with disruption of supply and rising fuel prices, fossil fuel gasification might hold good cards.

The recent increase in interest for advanced options has been mainly present in research and development. For both IGCC and transport fuels applications conquering a market segment will be very difficult, given its current status of high-risk high-(initial)-cost technology. The technology seems to be lacking the strong commitment that coal gasification does receive – or it receives these from countries (Sweden, Finland) which have significant lower RD&D budgets, industry and market potential compared to those supporting coal gasification (USA, China). This is especially relevant if a fast implementation is to be achieved. Such a development should focus on involving the USA, Germany and Japan (and possibly China), as patents suggest they hold the relevant industrial companies.

Given its currents status and support as well as the status of competing technologies, we seriously doubt that biomass gasification will meet the high expectations. It seems to be overly optimistic and probably mainly serves the advocacy coalition of the technology in embracing the technology and building up momentum for further development. We consider a process of gradual development in niches with limited market diffusion much more likely for the upcoming years.

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